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Flow and heat transfer characteristics of nanofluids containing rod-like particles in a turbulent pipe flow

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ABSTRACT

Numerical simulations of water-based ZnO nanofluids containing rod-like nanoparticles in a turbulent pipe flow are performed by solving the modified equations of Reynolds averaged Navier–Stokes, turbulence kinetic energy and turbulence dissipation rate with rod-like nanoparticle term, the general dynamic equation for rod-like nanoparticles and the equation describing the probability density functions for the rod-like nanoparticle orientation. Some results are validated by comparing with the available experimental or numerical results. The results show that the friction factor of nanofluids, being larger than that of the pure water, decreases with increasing Reynolds number and particle aspect ratio, and decreases when particle volume concentration Φ is changed from 0.4 v% to 0.93 v% and then increases when Φ is changed from 0.93 v% to 1.3 v%. The heat transfer of nanofluids is higher than that of the pure water. The ratios of Nusselt number for the nanofluid and pure water increase with increasing Reynolds number, particle aspect ratio and volume concentration. The ratios of energy performance evaluation criterion (PEC) for the nanofluids and pure water, PEC_{nf}/PEC_f, are less and larger than unity when $Re < 10{,}000$ and $Re > 10{,}000$, respectively. The values of PEC_{nf}/PEC_f increase with increasing the particle aspect ratio, and are not monotonously dependent on the particle volume concentration. It is more effective to use nanofluids containing rod-like nanoparticles with larger aspect ratio, at higher Reynolds number and at a suitable particle volume concentration. Finally the expressions of PEC_{nf}/PEC_f as a function of Reynolds number, particle volume concentration and particle aspect ratio are derived based on the numerical data.

1. Introduction

Nanofluid is a kind of fluid engineered by dispersing nano-sized materials, e.g. nanoparticles, nanorods, nanotubes and so on, in base fluid. Up to now, more and more attentions have been paid to the potentials of nanofluid in the practical applications among which the heat transfer enhancement is the most significant issue. It has been demonstrated by many researchers that suspending nano-sized particles to the conventional fluids can enhance the heat transfer [1–13]. Although the past research activities were focused on the investigations of nanofluids with spherical nanoparticles, the influence of nanoparticle shape on the heat transfer has attracted attentions because it has been shown that the heat transfer characteristics of nanofluid is sensitive to nanoparticle shape [14,15]. There has been some literature on the heat transfer of nanofluids containing non-spherical particles. Yang et al. [16] found that the disk-like graphite nanoparticle alignment disrupts the interaction particles and results in the deterioration of convective heat transfer. Timofeeva et al. [17] showed that the increases of the effective thermal conductivities due to particle shape effects expected from Hamilton–Crosser equation were diminished by interfacial effects proportional to the surface area of nanoparticles. Xie et al. [18] demonstrated that, for the nanofluids containing diamond nanoparticles, the convective heat transfer coefficient first increases with the increase of volume fraction, and then decreases with a further increase in the volume fraction. Ji et al. [19] found that the heat transfer was enhanced most strongly for rod-like particles followed by blade, plate, and brick shaped ones, respectively. But for larger heat loads, the brick particles performed best followed by rod-like, plate, and blade shaped ones, respectively. Jeong et al. [20] found that the thermal conductivity increased by up to 12% and 18% at 5.0 v% for the ZnO/water

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nanofluid containing spherical and nearly rectangular shape nanoparticles, respectively, compared to that of the base fluid.

Among the non-spherical particles the rod-like particles are the most common used particles. Compared with the spherical particles, it is more difficulty to deal with the rod-like particles because both the spatial and orientation distributions of particles affect the pressure drop and heat transfer characteristics. For example, rod-like particles would be expected to generate anisotropic stresses not observed using spherical particles. There have been several attempts to study the heat transfer characteristics of nanofluids containing rod-like particles. Masuda et al. [21] and Xie et al. [22] found that the rod-like SiC nanoparticles showed an enhancement of thermal conductivity over the spherical particles because a mesh produced by the elongated particles that conducts heat through the fluid. Murshed at al. [23] showed that, for the nanofluids containing TiO_2 nanorods with aspect ratio of 4, the thermal conductivity increase is nearly 33% over the pure water with 5% volume fraction. Murshed et al. [24] found that the thermal conductivity of nanofluids having rod-like particles was substantially higher than that of the base fluids, and was enhanced with increasing the particle volume fraction. Nelson et al. [25] showed experimentally that, in a plain offset fin heat exchanger using Polyalphaolefins nanofluids synthesized with exfoliated graphite fibers, the enhancement of convective heat transfer was caused by the precipitation of particles on the wall of the heat exchanger. Yu et al. [26] found that the particle aspect ratio, dispersion and aggregation affect significantly the effective thermophysical properties of Polyalphaolefins–Al_2O_3 nanofluids containing rod-like particles because the shear-induced alignment of the rod-like particles have an important effect on the heat transfer characteristics. Elias et al. [27] showed that, in a shell and tube heat exchanger, the rod-like particles exhibited the best heat transfer characteristics and rate among the five kind of nanoparticles with different shapes. In addition, the entropy generation for nanofluids containing rod-like particles was higher compared with the other particle shapes. Ooi and Popov [28] found that the nanoparticles with different shapes and sizes have different effects on the thermal conductivity of the Cu–water nanofluids, and the oblate spheroid with aspect ratio of 10 enhanced the heat transfer characteristics most obviously. Ghosh et al. [29] demonstrated that the heat transfer in the collision of a rod-like particle with a heat source under a definite condition was much higher than that for a spherical particle with same volume. Elias et al. [30] found that rod-like particles have the best overall heat transfer coefficient and rate among the other shapes. Lin et al. [31] showed that, for the Polyalphaolefins–Al_2O_3 nanofluids containing rod-like nanoparticles in a laminar pipe flow, the Nusselt number of nanofluids was directly proportional to the Reynolds number, particle volume concentration and particle aspect ratio.

It is an important issuer whether any gain in heat transfer will be compromised by an increase of pumping power. As shown above, the heat transfer of nanofluids with rod-like nanoparticles was higher not only than the values of the base fluids but also than that of nanofluids with spherical nanoparticles. Compared to numerous researches on the heat transfer, the flow characteristics of nanofluids with rod-like nanoparticles, for example, the friction factor and pressure drop, have been rarely reported. There was only some research literature on the laminar flow. Yu et al. [26] measured the pressure drop and indicated that the shear induced alignment and orientational motion of the rod-like particles should be taken into account in interpreting correctly the experimental data. Bozorgan et al. [32] showed that the pressure drop of nanofluid is slightly higher than water and increases with increase of volume concentrations. Ferrouillat et al. [33] defined an energy performance evaluation criterion to compare heat transfer rate to pumping power, and showed that only nanofluids containing ZnO nanoparticles with a shape factor greater than 3 attain a performance evaluation criterion as high as that of water. Lin et al. [31] found that the friction factor decreases with increasing Reynolds number, and the relationships between the friction factor and the particle volume fraction as well as aspect ratio are dependent on the Reynolds number. However, the turbulent flow is the most common form of motion of fluids playing the role of the heat-transfer medium in thermal systems. The addition of rod-like nanoparticles may affect the overall efficiency of the turbulent flow systems. In order to further understand the performance of nanofluids with rod-like nanoparticles as a heat transfer medium, studies should be done for the friction factor and pressure drop in the nanofluids. Therefore, the present paper aims to clarify the effect of the Reynolds number, nanoparticle volume fraction and aspect ratio on the heat transfer and friction factor characteristics of water-based ZnO nanofluids with rod-like nanoparticles in a turbulent pipe flow. We choose water-based ZnO because the thermal conductivity of ZnO is rather high and has been used widely, moreover, there exist some experimental results which can be taken to compare with the numerical results.

2. Basic equations

2.1. Governing equations with the additional term of rod-like nanoparticles

For the incompressible and fully developed flow, the governing equations are the continuity equation, modified Navier–Stokes equation [34] and the energy conservation equation with the additional term of rod-like nanoparticles:

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_{nf}} \frac{\partial p}{\partial x_i} + \frac{\mu}{\rho_{nf}} \frac{\partial^2 u_i}{\partial^2 x_j} + \frac{\mu_a}{\rho_{nf}} \times \frac{\partial}{\partial x_j}\left[a_{ijkl}\varepsilon_{kl} - \frac{1}{3}(I_{ij}a_{kl})\varepsilon_{kl}\right], \tag{2}$$

$$\frac{\partial T}{\partial t} + u_j \frac{\partial T}{\partial x_j} = (C_{nf} + C_T)\frac{\partial^2 T}{\partial x_j^2}, \tag{3}$$

in which u_i, p, T and ρ_{nf} are the nanofluid velocity, pressure, temperature and density, respectively; μ is the fluid viscosity; C_{nf} is the thermal diffusivity coefficient of the nanofluid; $\varepsilon_{ij} = (\partial u_i/\partial x_j + \partial u_j/\partial x_i)/2$ is the rate-of- strain tensor; a_{kl} and a_{ijkl} are the second- and fourth-order tensors of rod-like particle orientation, respectively; $C_T = C_\mu k^2/\varepsilon Pr_T$ (k is the turbulent kinetic energy, ε is the turbulent dissipation rate, C_μ = 0.09 and turbulent Prandtl number Pr_T = 0.9) is the eddy thermal diffusivity coefficient; μ_a is a function of the particle concentration and aspect ratio as well as the particle orientation distribution, and can be given by extending Batchelor's theory to account for two-body interactions [35]:

$$\mu_a = \frac{4\Phi_e\lambda^2\mu}{3\ln(1/\Phi_e)}\left\{1 - \frac{\ln[\ln(1/\Phi_e)]}{\ln(1/\Phi_e)} + \frac{0.6634}{\ln(1/\Phi_e)}\right\}, \tag{4}$$

where Φ_e is the effective particle volume fraction, λ is the particle aspect ratio.

For the turbulent flow we separate the instantaneous velocity, pressure, temperature, rate-of-strain tensor and tensors of particle orientation into mean and fluctuation part, and then substitute these variables into Eqs. (1)–(3) and average, Eqs. (1)–(3) become:

$$\frac{\partial U_i}{\partial x_i} = 0, \tag{5}$$